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Controls on intrusion of near-trench magmas of the Sanak-Baranof belt, Alaska, during Paleogene ridge subduction, and consequences for forearc evolution

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ABSTRACT

A belt of Paleogene near-trench plutons known as the Sanak-Baranof belt intruded the southern Alaska convergent margin. A compilation of isotopic ages of these plutons shows that they range in age from 61 Ma in the west to ca. 50 Ma in the east. This migrating pulse of magmatism along the continental margin is consistent with North Pacific plate reconstructions that suggests the plutons were generated by migration of a trench-ridge-trench triple junction along the margin. On the Kenai Peninsula the regional lower greenschist metamorphic grade of the turbiditic host rocks, texture of the plutons, contact-metamorphic assemblage, and isotopic and fluid inclusion studies suggest that the plutons were emplaced at pressures of 1.5–3.0 kbars (5.2–10.5 km) into a part of the accretionary wedge with an ambient temperature of 210–300 °C. The presence of kyanite, garnet, and cordierite megacrysts in the plutons indicates that the melts were generated at a depth greater than 20 km and minimum temperature of 650 °C. These megacrysts are probably xenocrystic remnants of a restitic or contact metamorphic phase entrained by the melt during intrusion. However, it is also possible that they are primary magmatic phases crystallized from the peraluminous melt.

Plutons of the Sanak-Baranof belt serve as time and strain markers separating kinematic regimes that predate and postdate ridge subduction. Pre-ridge subduction structures are interpreted to be related to the interaction between the leading oceanic plate and the Chugach terrane. These include regional thrust faults, NE-striking map-scale folds with associated axial planar foliation, type-1 mélanges, and an array

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of faults within the contact aureole indicating shortening largely accommodated by layer-parallel extension. Syn-ridge subduction features include the plutons, dikes, and ductile shear zones within contact aureoles with syn-kinematic metamorphic mineral growth and foliation development. Many of the studied plutons have sheeted margins and appear to have intruded along extensional jogs in margin-parallel strike-slip faults, whereas others form significant angles with the main faults and may have been influenced by minor faults of other orientations. Some of the plutons of the Sanak-Baranof belt have their long axes oriented parallel to faults of an orthorhombic fault set, implying that these faults may have provided a conduit for magma emplacement. This orthorhombic set of late faults is interpreted to have initially formed during the ridge subduction event, and continued to be active for a short time after passage of the triple junction. ENE-striking dextral faults of this orthorhombic fault system exhibit mutually crosscutting relationships with Eocene dikes related to ridge subduction, and mineralized strike-slip and normal faults of this system have yielded $^{40}Ar/^{39}Ar$ ages identical to near-trench intrusives related to ridge subduction. Movement on the orthorhombic fault system accommodated exhumation of deeper levels of the southern Alaska accretionary wedge, which is interpreted as a critical taper adjustment to subduction of younger oceanic lithosphere during ridge subduction. These faults therefore accommodate both deformation of the wedge and assisted emplacement of near-trench plutons. Structures that crosscut the plutons and aureoles include the orthorhombic fault set and dextral strike-slip faults, reflecting a new kinematic regime established after ridge subduction, during underthrusting of the trailing oceanic plate with new dextral-oblique convergence vectors with the overriding plate. The observation that the orthorhombic fault set both cuts and is cut by Eocene intrusives demonstrates the importance of these faults for magma emplacement in the forearc.

A younger, ca. 35 Ma suite of plutons intrudes the Chugach terrane in the Prince William Sound region, and their intrusion geometry was strongly influenced by pre-existing faults developed during ridge subduction. The generation of these plutons may be related to the sudden northward migration of the triple junction at ca. 40–33 Ma, as the ridge was being subducted nearly parallel to the trench during this interval. These younger plutons are used to provide additional constraints on the structural evolution of the wedge. Late- to post-ridge subduction fabrics include a pressure solution cleavage and additional movement on the orthorhombic fault system. After triple junction migration, subduction of the trailing oceanic plate involved a significant component of dextral transpression and northward translation of the Chugach terrane. This change in kinematics is recorded by very late gouge-filled dextral faults in the late structures of the accretionary prism.

Keywords: Sanak-Baranof belt, Alaska, near-trench magmas, forearc, ridge subduction, Kenai Peninsula, xenocryst.

INTRODUCTION

Forearc regions are normally relatively "cold" places under tectonic compression, yet a few contemporary forearc accretionary prisms contain numerous granitoid intrusions (Pitcher, 1983). Ridge subduction has been invoked to explain the presence of near-trench magmas in several forearc regions (e.g., Marshak and Karig, 1977; Dixon and Farrar, 1980; Bradley et al., 1993; Sisson and Pavlis 1993) as well as anomalous deformation, thermal signatures, and landward structural vergence in accretionary prisms (e.g., Hibbard and Karig, 1990; Lallemand et al., 1992; Kusky et al., 1997a, 1997b).

Near-trench magmatic rocks appear in most cases to represent a mixture of MORB components from the subducted ridge contaminated by a sedimentary component of the overriding accretionary prism (Moore et al., 1983; Hibbard and Karig, 1990; Harris et al., 1996; Maeda and Kagami, 1996; Lytwyn et al., 2000; Sisson et al., this volume, Chapter 13), although an arc-like component has been recognized in the Woodlark near-trench magmas (Perfit et al., 1987; Johnson et al., 1997). Metamorphic signatures associated with ridge subduction are known to include high-temperature, low-pressure metamorphic facies as documented in the Chugach metamorphic complex (Hudson and Plafker, 1982; Hudson et al., 1979; James et al., 1989; Sisson and

Hollister, 1988; Sisson et al., 1989). Structural signatures of the subduction of ridges have received slightly less attention with most data derived from active examples, simply because it is difficult to relate specific structures in ancient accretionary prisms to ridge subduction events (Vogt et al., 1976; Furlong et al., 1989; Thorkelson and Taylor, 1989; Hibbard and Karig, 1990; von Huene and Lallemand, 1990; Lallemand et al., 1992; Kusky et al., 1997a, 1997b; Kusky and Young, 1999).

Here, we document aspects of the structural history of an accretionary prism before, during, and after ridge subduction. We use plutons that are believed to have been generated by passage of the triple junction (see Bradley et al., 1993, this volume, Chapter 1) as a time marker separating different kinematic regimes to evaluate the structural history before, during, and after ridge subduction. We also examine faults associated with gold-quartz mineralization formed during ridge subduction. The strain history recorded by the plutons is somewhat different from the gold-quartz veins/faults (Haeussler et al. this volume). The plutons can also be utilized as strain markers injected into the wedge between two different kinematic regimes, including (a) interactions of the "oceanic plate A"—North America plates prior to ridge subduction, and (b) interaction of the "oceanic plate B"—North America plates after ridge subduction. We refer to the leading, eastern oceanic plate that was subducted before passage of the triple junction as oceanic plate A, and the western or trailing oceanic plate that was subducted after ridge subduction as oceanic plate B. This is because the record of a similar-age ridge subduction event in the Olympic Mountains (Wells et al., 1984; Babcock et al., 1992, 1994) raises some uncertainty as to whether the ridge subduction record in southern Alaska is a product of subduction of the Kula-Farallon ridge or a ridge between the Kula and another smaller plate to the east (Bradley et al., 1993, this volume, Chapter 1), colloquially named the Resurrection plate by Haeussler et al. (2000). Understanding the kinematic framework that predates and postdates pluton emplacement, on local scales, can thus be used to infer the larger-scale change in kinematics associated with passage of the triple junction. In the following sections, we document structures that predate and postdate the ca. 56.0 ± 0.3 Ma (U-Pb on monazite, Bradley et al., 2000) Nuka, Tustumena–Harris Bay, and Aialik plutons, and we relate these to subduction of oceanic plates A and B, respectively. We do the same for a suite of ca. 35 Ma plutons that intrude the accretionary prism in the Prince William Sound area and offer a model for the tectonic origin of these Late Eocene plutons that also relates to ridge subduction. We also document and discuss mechanisms of emplacement of these plutons, as the intrusion mechanisms are directly related to the mechanics of ridge subduction.

REGIONAL GEOLOGY

Southern Alaska is composed of a series of accreted terranes representing relict Paleozoic, Mesozoic, and Cenozoic arc-trench systems, oceanic plateaus, and flysch basins (Plafker et al., 1989). The Chugach–Prince William composite terrane (Fig. 1) is over 2200 km long and extends from Baranof Island in southeastern Alaska westward to Valdez and then southwestward to the Sanak and Shumagin Islands. It consists of deformed Triassic-Cretaceous mélange with exotic blocks of Permian limestone, Upper Cretaceous–Tertiary flysch with minor tholeiitic volcanic rocks, and a thin discontinuous band of dismembered ophiolites (Nelson et al., 1985; Bol et al., 1992; Nelson and Nelson, 1993; Crowe et al., 1992; Kusky et al., 1997a, 1997b; Kusky and Young, 1999).

Triassic-Cretaceous mélange in the Chugach terrane is known as the McHugh Complex in the Chugach Mountains (Clark, 1972; Bradley and Kusky, 1990, 1992; Kusky et al., 1997b; Kusky and Bradley, 1999). The McHugh Complex has been regionally metamorphosed to prehnite-pumpellyite facies (Clark, 1972; Kusky et al., 1997a), consistent with pressures of 3–8 kbars and burial to 11–30 km at relatively low temperatures. A second component of the Chugach terrane consists of deformed Cretaceous flysch known as the Valdez Group (Tysdal and Plafker, 1978; Nilsen and Zuffa, 1982; Kusky et al., 1997b) metamorphosed to lower-greenschist grade (Bradley et al., 1999). Hawley (1992) and Fisher and Brantley (1992) suggest that there has been a large-scale mobilization of many elements because sericite and chlorite occur in quartz/calcite veins. They suggest a minimum temperature of 200 °C for the deformation and alteration since albite precipitated in equilibrium with sericite and is not stable below that temperature. Goldfarb et al. (1986), Borden et al. (1992) and Taylor et al. (1994) report isotopic and fluid inclusion data from ca. 55 Ma quartz veins in the region showing that the veins (and presumably the related plutons) were emplaced at 1.5–3.0 kbars (5.2–10.5 km) at temperatures of 210–300 °C.

Paleogene flysch in the Prince William terrane is known as the Orca Group (Moffit, 1954; Plafker, 1987; Kveton, 1989). Scarce fossils indicate that portions of the Valdez Group is Late Cretaceous (Maestrichtian) in age (Jones and Clark, 1973; Bradley et al., 1999) while the Orca Group ranges in age from Paleocene to early Eocene (Winkler, 1976; Tysdal and Case, 1979; Tysdal et al., 1977). The Valdez and Orca metasedimentary rocks contain lode gold deposits that occur in quartz dikes and veins as free metals or combined with sulfides (Tuck, 1933; Silberman et al., 1981; Goldfarb et al., 1986; Stüwe, 1986; Haeussler et al., 2000, this volume). An anomalous high-temperature, low-pressure metamorphic belt has been well documented in the eastern Chugach Mountains (Pavlis et al., 1988; Sisson et al., 1989, this volume, Chapter 13).

Early Tertiary near-trench intrusive rocks are widespread in the Chugach accretionary wedge. They belong to what Hudson (1983) named the Sanak-Baranof belt, a 2200 km long belt including biotite-muscovite granodiorites, leucotonalites, trondhjemites, and dikes ranging in composition from basalt to rhyolite (Marshak and Karig, 1977; Hill, 1979; Hill et al., 1981; Barker et al., 1992; Bradley and Kusky, 1992). The plutons, plugs, dikes, and sills lie far outboard of an evidently

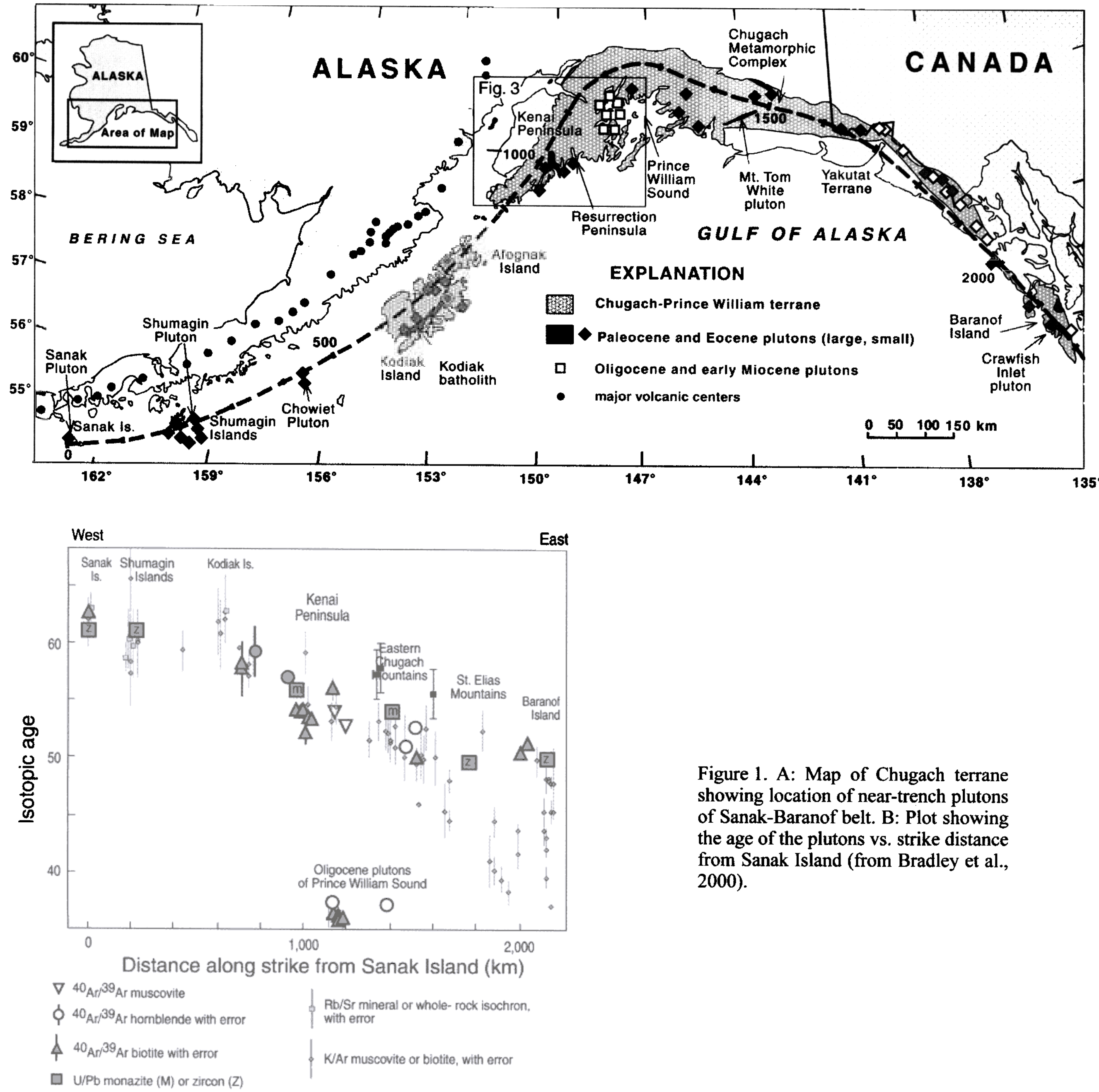

Figure 1. A: Map of Chugach terrane showing location of near-trench plutons of Sanak-Baranof belt. B: Plot showing the age of the plutons vs. strike distance from Sanak Island (from Bradley et al., 2000).

coeval magmatic arc (Fig. 1). They intrude trench deposits and ophiolite fragments that had only been deposited and offscraped a few million years earlier (Kusky and Young, 1999). The age of near-trench magmatism decreases from west to east around the Gulf of Alaska, from 61 Ma at Sanak and the Shumagins to ca. 50 Ma at Baranof Island (Bradley et al., 1993, 2000). One interpretation of the near-trench magmatism is that it marks the site of subduction of an oceanic ridge. The age progression (Fig. 1B), then, is interpreted to track the migration of the triple junction (Fig. 2) (Bradley et al., 1993, 2000).

GRANITE OF THE HARDING ICEFIELD REGION

A remote area on the outer Kenai Peninsula between the Harding Icefield and the Pacific Ocean hosts several large plutons and numerous small stocks and plugs of the Sanak-

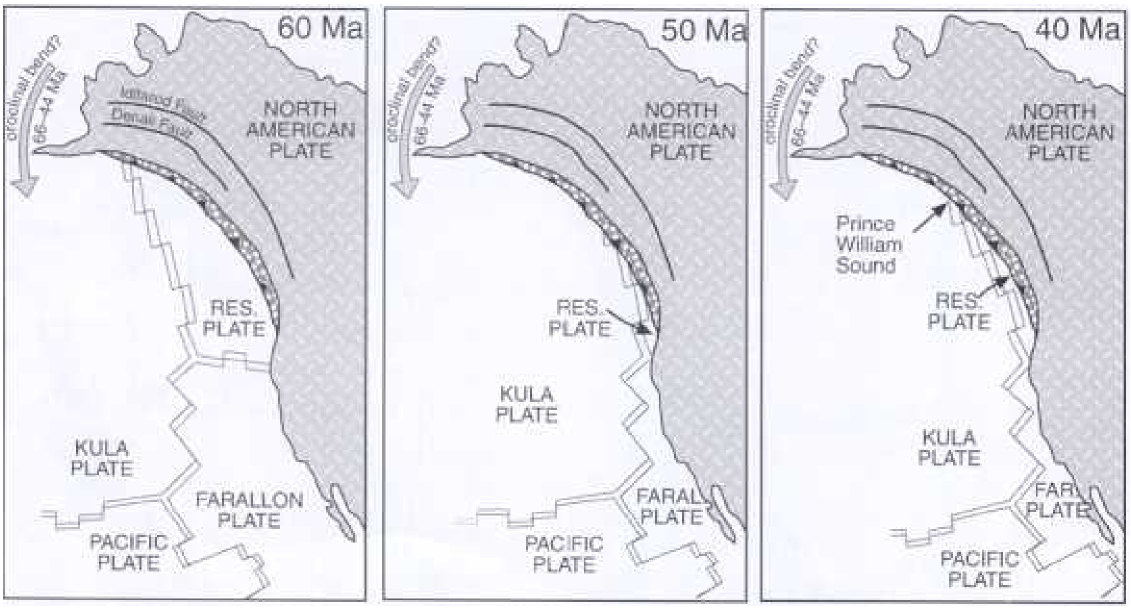

Figure 2. Schematic plate reconstructions, showing the Kula–Resurrection (Oceanic plate B)–North America triple junction moving southward along the margin from 60 to 50 Ma, then jumping back north by 40 Ma in response to the early Eocene plate reorganization. See Bradley et al. (this volume, Chapter 1) for alternative plate reconstructions. In each of the time intervals, the entire Alaskan orocline is shown as partly straightened out, and the Chugach–Prince William terrane is restored by ~820 km southward along the margin. Reconstruction at 60 Ma is from Bradley et al. (this volume, Chapter 1).

Baranof belt (Figs. 1 and 3). Martin et al. (1915) were the first to map the rocks of the Kenai Peninsula, followed by Cowan and Boss (1978), Magoon et al. (1976), Tysdal and Case (1979), and Bradley et al. (1999). Martin et al. (1915) suggested that because the plutons truncate folded sedimentary rocks thought to be Jurassic to Cretaceous, they are probably Tertiary. Tysdal and Case (1979) named these plutons the "granite of the Harding Icefield region" and suggested that the granite forms a batholith that extends into the Seldovia quadrangle to the west and northward ~50 km, outcropping discontinuously as nunataks in the Harding Icefield (Figs. 4 and 5A). Bradley et al. (1999) mapped the granitoids and surrounding rocks in the Seldovia quadrangle, documenting the southern and western extent of the granitic rocks. Bradley and Wilson (2000) traced the pluton into the Kenai quadrangle. Compositions vary from tonalite near the contacts through granite in the pluton interior (Bradley et al., this volume, Chapter 1). Tysdal and Case (1979) report that the contacts between the batholith and country rock are steeply dipping, and dominantly bedding parallel, although some contacts are discordant (Fig. 4).

The Nuka, Aialik, Harris Bay, and Tustumena plutons are the main plutonic components of the "granite of the Harding Icefield" (Fig. 4) and together form one of the largest (>2500 km^2) near-trench igneous complexes in the Sanak-Baranof belt, and apparently in the world. The Kodiak Batholith on Kodiak Island is longer, but much thinner, making it smaller in area (1650 square km) than the plutonic complex of the Harding Icefield. The Nuka and Aialik plutons have broadly ovoidal shapes that are elongate nearly parallel to the grain of accreted rocks, but the Tustumena–Harris Bay complex forms a significant angle with earlier structures (Fig. 4).

The Nuka pluton crops out from Nuka Bay to Thunder Bay (Figs. 3 and 4). The Nuka pluton has yielded an U/Pb (zircon and monazite) age of 56 ± 0.5 Ma (Bradley et al., 2000), and a $^{40}Ar/^{39}Ar$ age spectrum that is a plateau corresponding to an isochron age of 54.2 ± 0.08 Ma (Bradley et al., 2000). The Nuka pluton is a buff-rust weathering massive, coarse to finely crystalline, granitic rock with abundant euhedral plagioclase feldspar and quartz, lesser and varying amounts of potassium feldspar, muscovite, chlorite, and a few percent of mafic minerals including hornblende and biotite. Near the contact with the country rocks, the Nuka pluton is a fine-grained, well-foliated tonalite that forms numerous tabular dikes and sills crosscutting the country rock (Fig. 5B). This is in sharp contrast to the coarse-grained, orthoclase-rich, granodiorite in the center of the pluton. Metasedimentary and gabbroic xenoliths form minor but ubiquitous components of the Nuka pluton (Fig. 5C) and large xenocrysts of kyanite are present (Fig. 5D). The pluton exhibits a moderately strong magmatic foliation (defined by long axes of plagioclase and rarely hornblende, and aligned biotite) and a moderately to strongly developed tectonic foliation (defined by biotite and recrystallized quartz ribbons). In most places in the

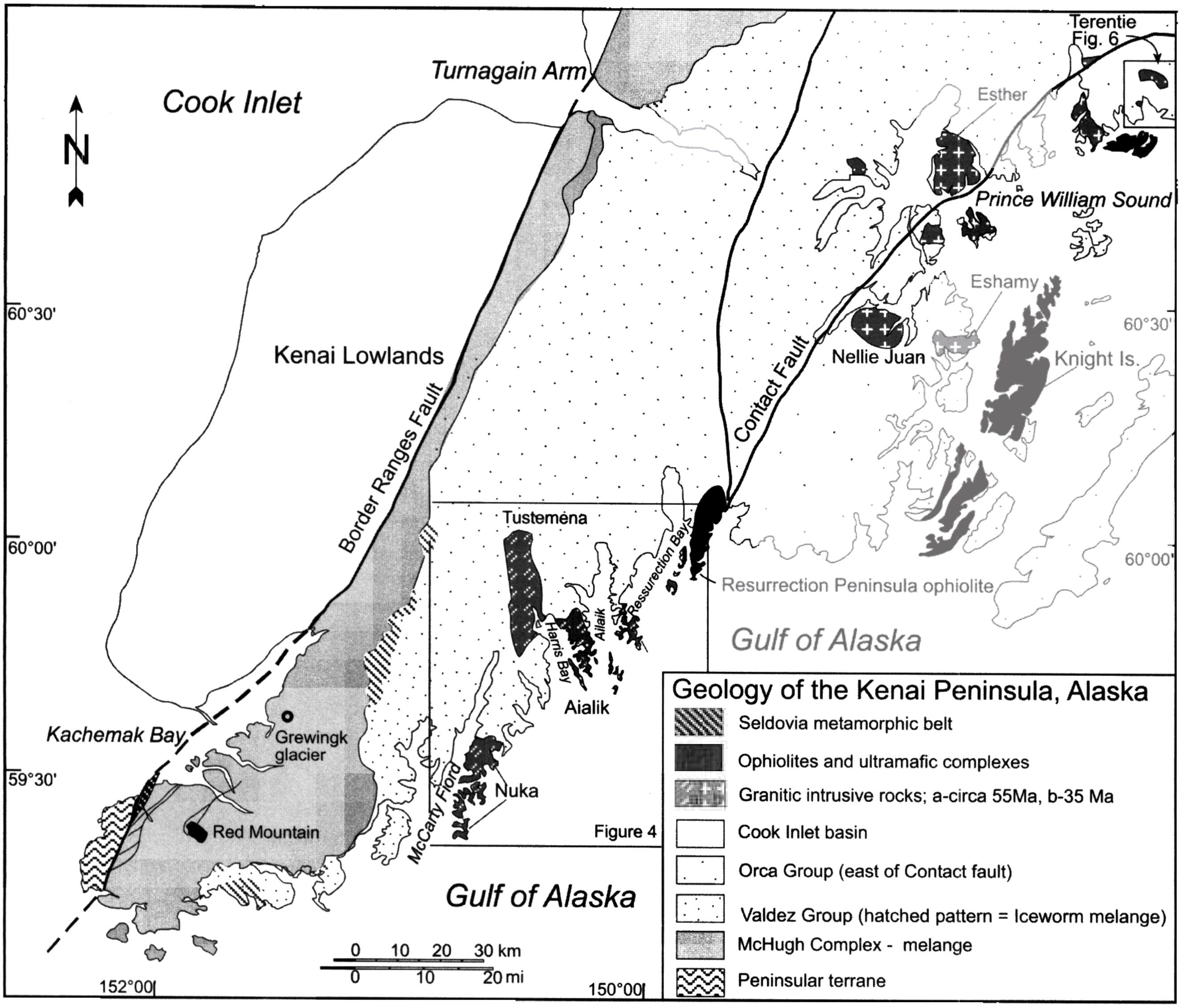

Figure 3. Simplified geologic map of the Kenai Peninsula, showing the setting of the Nuka, Aialik, Harris Bay, Terentiev, and related plutons.

Nuka pluton, the coaxial magmatic and tectonic foliation strike parallel to the long axis of the pluton, are steeply dipping, and contain a gently north-plunging lineation (Fig. 4).

The Tustumena–Harris Bay pluton forms a continuous S-shaped intrusive complex, with a sharp bend centered on the head of Harris Bay in Northwestern Lagoon (Fig. 4). The Tustumena–Harris Bay pluton is spectacularly exposed on small nunataks, and in the fiords of Northwestern Lagoon (Fig. 4), but is largely buried by ice. Contacts shown on the map (Fig. 4) are based on detailed mapping that include many small nunataks, too small to show on the map at this scale (see http://wrgis.wr.usgs.gov/open-file/of99-18/). The pluton has yielded a $^{40}Ar/^{39}Ar$ plateau age on biotite of 53.23 ± 1.14 Ma (Bradley et al., 2000), whereas a biotite separate from the Harris Bay lobe analyzed at University of Alaska, Fairbanks, yielded three plateau ages: 51.1 ± 0.5, 53.5 ± 0.5, and 49.6 ± 1.7 Ma (Bradley et al., 2000). The variation may be due to the presence of a small amount of excess argon. The Tustumena–Harris Bay pluton is a medium- to coarse-grained granodiorite containing biotite, muscovite, rare hornblende, and xenocrystic kyanite (Donley et al., 1995). Tysdal and Case (1979) reported subordinate granitic and tonalitic phases. The pluton locally displays a tectonic foliation that also affects aplitic dikes (Fig. 5E). The granodioritic rocks in the area of the bend in NW Lagoon are much more strongly deformed than typical granites of the Harding Icefield region, and they display both magmatic and crystal-plastic

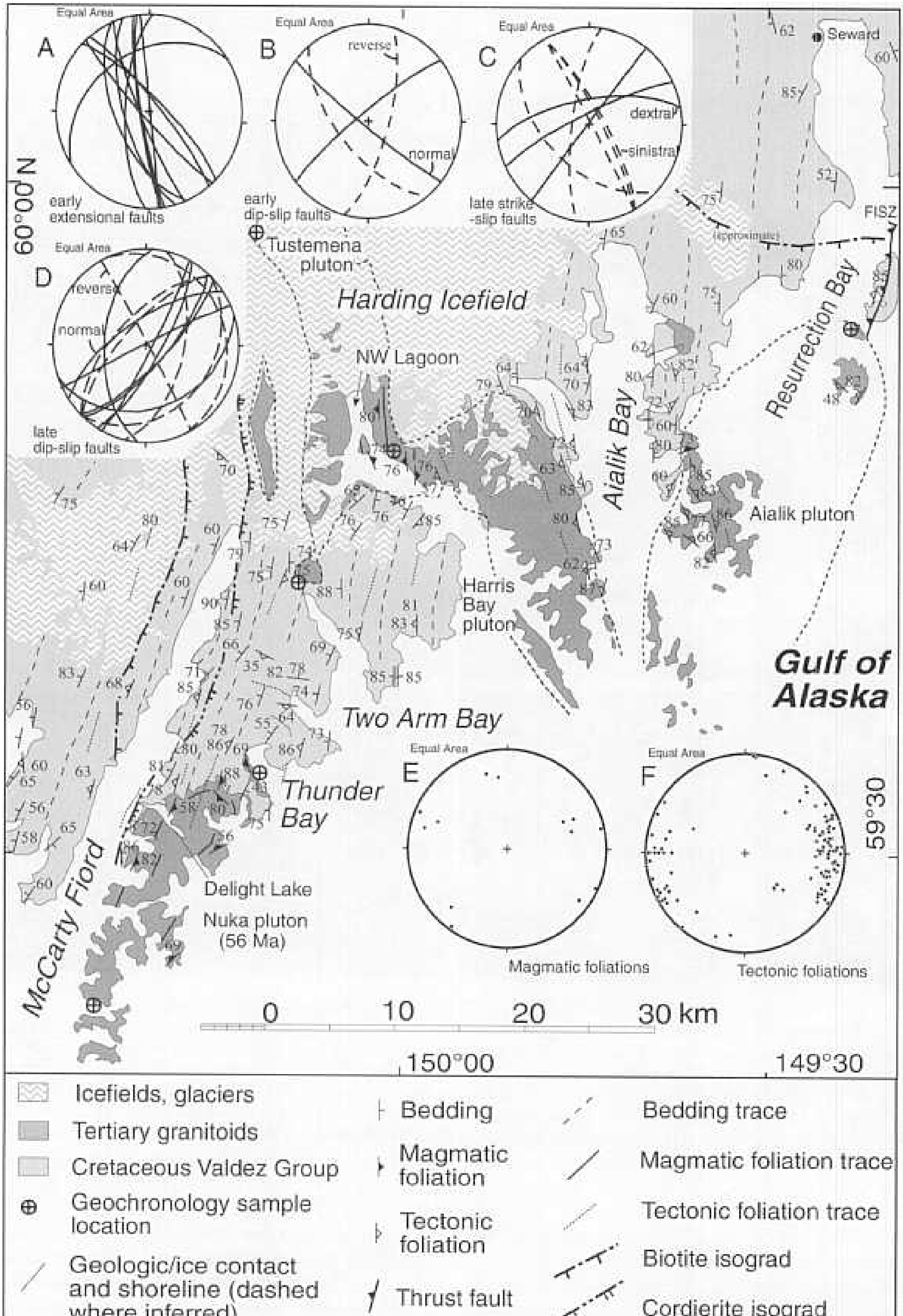

Figure 4. Structural map of the Nuka–Aialik–Harris Bay plutons, showing relationships between magmatic and tectonic foliations. The western half of the map is simplified from Bradley et al. (1999), and the eastern half is based on the map of Tysdal and Case (1979). Both maps were supplemented with additional mapping and detailed field observations, and contacts between plutons and country rocks are largely interpreted based on these observations. Insets are lower-hemisphere, equal-area projections showing the orientations of brittle fractures in and around the Nuka and Aialik plutons. Early faults predate pluton emplacement, late faults postdate pluton emplacement. A: Early orogen-parallel extension fractures. B: Early high-angle dip-slip faults (reverse dashed, normal solid). C: Late strike-slip faults (sinistral dashed, dextral solid). D: Late dip-slip faults (normal solid, reverse dashed). E: Magmatic foliations. F: Tectonic foliations.

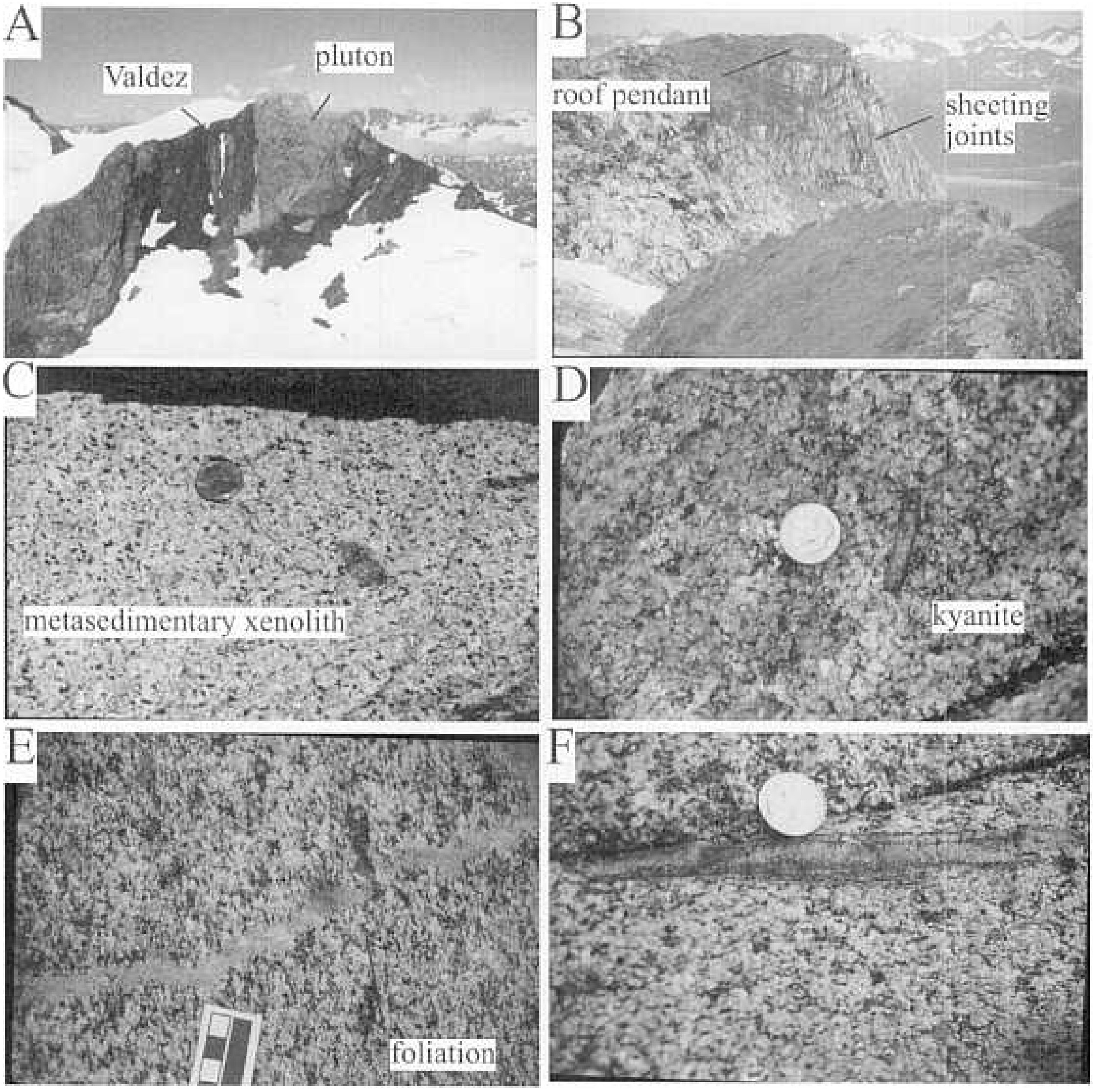

Figure 5. Field photographs. A: Contact of Tustumena pluton and Valdez Group exposed on Nunatak in the Harding Icefield. B: Nuka pluton (Delight Lake in background) showing vertical sheeting joints and roof pendant of Valdez Group. C: Metasedimentary xenolith in Aialik pluton. D: Kyanite xenocryst in Nuka pluton. E: Foliated granodiorite and aplite dike in Tustumena–Harris Bay pluton, from shear zone in Harris Bay. F: Foliated granodiorite and metasedimentary xenolith from Tustumena–Harris Bay pluton in Harris Bay. G: Dikes related to plutons. H: Tertiary dike cutting foliation of Iceworm mélange. I: Foliated dike. J: Apophysis from dike that cuts foliation but is apparently folded. K: Faulted dike from Grewingk Glacier. L: Plug of granodiorite from Crow Pass (Turnagain Arm) showing large stoped block.

deformation fabrics (Figs. 5E and 5F). These foliations are parallel to the long axis of the Tustumena lobe of the pluton.

The Aialik pluton outcrops discontinuously around the mouth of Resurrection Bay and Aialik Bay, and has an unknown contact relationship with the Harris Bay pluton (Fig. 4). A biotite separate from the northern part of the Aialik pluton on Hive Island yielded a $^{40}Ar/^{39}Ar$ plateau age of 53.4 ± 0.4 Ma (Bradley et al., 2000). The Aialik pluton is a massive rust-buff weathering, medium- to coarse-grained tonalite to granodiorite that has abundant shallowly dipping sheeting joints. Mineral percentages range from 30 to 45% plagioclase, 10–30% orthoclase, 20–30% quartz, 3–10% biotite, 3–7% amphibole, 1–4% muscovite, 0–5% chlorite, epidote, apatite, zircon, kyanite, garnet, sillimanite, cordierite, and opaques. It is nearly identical to the Nuka and Tustumena–Harris Bay plutons in mineral percentages and magmatic and tectonic fabrics, and it too contains gabbroic xenoliths that are elongate parallel to the magmatic foliation. It also contains metasedimentary xenoliths and megacrystic aluminosilicates

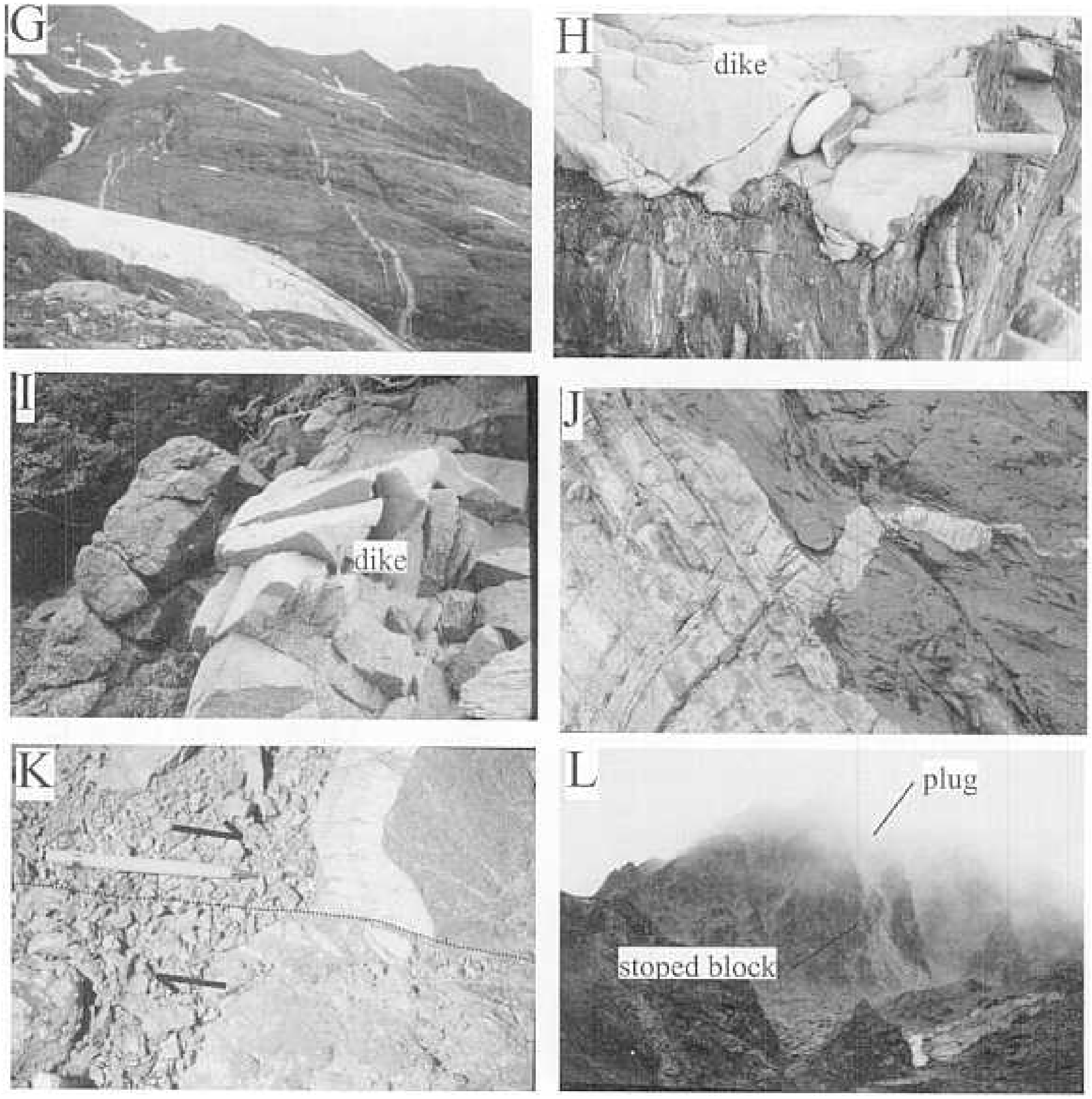

Figure 5 (*continued*).

(kyanite, cordierite), particularly along its margins. The only notable difference is that the Aialik pluton is locally very biotite-rich, with large (~2 cm), strongly aligned books of mica composing up to 20% of the rock. Both the Nuka and Aialik plutons contain several small, late stage, tourmaline-bearing pegmatites.

Between the Nuka and Tustumena–Harris Bay plutons, there are several smaller outcroppings of granitic rocks in Two Arm Bay (Paguna stock), Thunder Bay, and west of the area at Chernof Glacier (Figs. 1, 3, and 4; Bradley et al., 2000). The Chernof stock has yielded a $^{40}Ar/^{39}Ar$ biotite age of 54.2 ± 1.14 Ma, whereas the sill in Thunder Bay has a biotite $^{40}Ar/^{39}Ar$ plateau age of 53.7 ± 0.1 Ma (Bradley et al., 2000). Although these outcrops are not visibly part of the Nuka, Tustumena–Harris Bay, or Aialik plutons, their identical mineralogy, overlapping closure dates on biotite (Bradley et al., 2000), close proximity to much larger outcrops of granodiorite, and the fact that the bedrock separating the outcrops are thin ridges of high-grade hornfels suggest that they may be part of the same system of Paleogene plutons.

In all of the granitoids of the Harding Icefield region, plagioclase forms well-zoned framework grains that have a range of An content from 25 to 50%. The cores of the plagioclase have a patchy appearance due to later albitization. Many of the larger plagioclase grains, near the contact with country rock, show evidence of post-crystallization deformation including fractured grains, deformation twinning, offset albite twinning and rarely undulose extinction. Orthoclase, near the contact with country rock, rarely occurs as individual crystals but rather occurs as an orthoclase-quartz granophyric intergrowth between the plagioclase. Away from the contacts, orthoclase forms small euhedral crystals that in many cases are mantled around the much larger plagioclase laths. Quartz resides interstitially between the feldspars and mafic minerals. It is commonly deformed and/or recrystallized near the margins of the pluton and has a strong polycrystalline habit. Biotite occurs as large, partly euhedral mats and as a secondary mineral after amphibole, kyanite, and cordierite. High-Mg amphibole occurs as small anhedral crystals that show evidence of retrogression to biotite and chlorite. Muscovite is rarely primary, as it is secondary sericite after plagioclase and kyanite. Epidote occurs as small, zoned, euhedral to anhedral crystals, mantled in biotite and as an overgrowth on hornblende, that are found predominantly near the contact with the country rock. Kyanite forms large (>2.5 cm) megacrysts near the contact with the country rock, particularly in association with xenoliths (mostly metasedimentary). The kyanite has a reaction rim of andalusite, sillimanite, muscovite, biotite and chlorite (Donley et al., 1995). Additional work is needed on this assemblage to determine the reactions and *P-T-t* path followed by the kyanite crystals from their source to their final emplacement. Cordierite is found near the contact with the country rock as well, but typically forms much smaller, anhedral crystals found almost exclusively in the cores of large biotite crystals. The kyanite and cordierite phenocrysts have not been observed in the same sample, or to occur in any spatial or temporal relationship. Garnet is present in minor amounts in the plutons, but is more common in the dikes associated with the plutons.

Origin of Aluminosilicate Xenocrysts

Garnet and cordierite crystals are not uncommon in peraluminous granites. However, kyanite megacrysts are very rare in granitic magmas. Examples of granitic rocks bearing other aluminosilicate megacrysts are known from several places, including the Blue Mountains of northeastern Oregon (Johnson et al., 1997), and in the Grenville province (Perreault and Martignole, 1988). There are at least three possible origins for the large kyanite and other aluminosilicate megacrysts in the plutons of the Sanak-Baranof belt. First, they could be part of a restitic phase plucked from the wall rock in the granitic source region, and carried upward by the melt (e.g., Vernon, 1983). Partial melting of pelitic source rocks has been shown in several cases to generate trapped crystals of K-feldspar, garnet, cordierite, biotite, kyanite, spinel, sillimanite, and other minerals (e.g., Couturié, 1969; Tracy and Robinson, 1983; Clark and Lyons, 1986; Barbey, 1991; Hibbard, 1995). The reaction rims around the kyanite may have effectively isolated the kyanite xenocrysts from the melt so that they did not re-react with the melt to produce phases stable at lower pressures and temperatures. Reactions between magma and restitic xenocrysts are known to produce biotite-rich reaction rims around the inclusions (e.g., Couturié, 1969). In a similar way, the kyanite megacrysts might represent pieces of a contact metamorphic phase, plucked from the wall rocks during the magmas ascent and entrapped in the marginal phases of the plutons. This second process has been documented in Hercynian granites from the Central Iberian Massif (Ugidos, 1990; Recio et al., 1992; Ugidos and Recio, 1993).

The kyanite megacrysts in the Nuka and Aialik plutons could alternatively be a magmatic phase, because they occur only as large single megacrysts that have aspect ratios of up to 17:1, and none of the xenoliths spatially associated with the kyanites have kyanite as a constituent mineral. The kyanite has margaritic-kaolinitic exsolution-alteration along cleavage traces. In any case, the presence of the kyanite megacrysts indicate that the aluminous melt was generated at a depth exceeding 20 km at a minimum temperature of 650 °C (e.g., Essene, 1986; Spear, 1993; Hibbard, 1995). It is likely that the kyanite crystals were initially formed by heat from mafic intrusions generated from the slab window, which metamorphosed and partially melted the base of the accretionary prism. The hybrid magmas then rose to higher crustal levels, where they cooled and crystallized.

Magmatic and Tectonic Foliations in the Granite of Harding Icefield

Structural studies of the Nuka, Tustumena–Harris Bay, and Aialik plutons were undertaken to understand the mechanisms of intrusion of such large volumes of melt into an accretionary prism and to elucidate the effects of the incorporation of large plutonic bodies into the accretionary wedge. Emphasis was placed on determining relationships between fabrics of magmatic (pre-complete crystallization) and tectonic (hypersolidus, or crystal-plastic) origin, and establishing the relative timing of pluton emplacement and fabric development through examination of the geometrical relationships between foliations and porphyroblast growth in the contact aureoles of the plutons (e.g., Hutton, 1988; Dell'Angelo and Tullis, 1988; Paterson and Tobish, 1992). Relationships between plutons and regional structures were also examined. The sequence of crosscutting relationships within these plutons and their contact aureoles is used to determine the kinematic regime in the wedge before, during, and after pluton emplacement. Since the plutons are interpreted to be a consequence of ridge subduction, this information may be related to plate convergence parameters and wedge mechanics before, during, and after passage of the triple junction.

The plutons intrude the Cretaceous Valdez Group, which in the area is a thick sequence of turbiditic sandstone and shale with some minor granule conglomerate and calcareous siltstone (Dumoulin, 1987, 1988; Bradley et al., 1999; Kusky and Young, 1999). The Valdez Formation is locally transposed into a mélange (Iceworm mélange) (Kusky et al., 1997b) consisting of blocks of graywacke in a phacoidally cleaved argillite matrix. This mélange fabric is associated with the Chugach Bay thrust (Kusky et al., 1997b). In the area of study, the Valdez Formation turbidites are dominantly foliated, gray to black, variably silt-rich slate and phyllite interbedded with thin (1–6 cm) siltstone beds. The slates and sandstones are moderately recrystallized from regional metamorphism generally to lower greenschist facies, with muscovite, chlorite, quartz, albite, and minor calcite making up the bulk of the new minerals (Goldfarb et al., 1986; Gibbons, 1988; Bradley et al., 1999).

A regional contact aureole surrounds the Nuka, Tustumena–Harris Bay, and Aialik plutons. It includes a zone ranging from 5 to 25 km wide (Fig. 4), of lower greenschist to lower amphibolite facies meta-turbidites. The area between the Nuka pluton, Tustumena pluton, and the Aialik pluton (Fig. 4) is a large area of generally greenschist through amphibolite facies metamorphic rocks formed as a coalesced contact aureole from the numerous intrusions in this area. We refer to this area as the Kenai metamorphic complex, and note that it is similar to but at lower grade than the Chugach metamorphic complex in the northern Chugach Mountains (Sisson et al., 1989). The thickness and extent of this aureole in such a shallow crustal level suggests that the region may be underlain by numerous other plutons just below the surface, forming the regional contact aureole. On the northwest side of the Nuka pluton near Delight Lake (Fig. 4), the meta-sandstone and pelite have a purple color and a distinct lumpy appearance due to foliation-parallel biotite and cordierite porphyroblasts. Cordierite is surrounded by white mica that define a foliation-parallel stretching lineation, plunging gently north in most places, but with steep plunges in others. The cordierite has undergone syn-growth deformation as shown by asymmetric porphyroclast tails and inclusion patterns, as well as a strong polycrystalline habit. Within 100–1600 meters of the contact, cordierite is generally no longer present, but the hornfels are still biotite-rich, with minor muscovite, epidote, and calcite. The next 300–2600 meters is marked by a rapid decline in the percentage of biotite, and the rocks take on a blocky rusty weathering appearance and are green on fresh surfaces, reflecting the assemblage quartz, plagioclase, muscovite, chlorite, epidote, and calcite. The remaining contact aureole is a gradual transition to lower grades of regional metamorphism.

Figure 4 shows foliation orientations within the Nuka, Aialik, and Tustumena–Harris Bay plutons and the surrounding Valdez formation. The magmatic foliation is parallel to the intrusive contacts and generally trends ENE (Fig. 4). In many places along the margins of the Nuka pluton, the granodiorite forms steeply dipping magmatic sheets defined by the magmatic foliation (parallel to traces of magmatic foliation on Fig. 3, and shown as photo in Fig. 4B), but on the NE side of the pluton these sheets become subhorizontal. The majority of magmatic and tectonic foliations in the Nuka and Aialik plutons are subparallel to the intrusive contacts and regional structural trend (Fig. 4), although at the NE and SW ends of the plutons, the magmatic foliation and pluton contacts are discordant with the regional tectonic foliation. Dikes that stem from the northeastern contact of the Nuka pluton are oriented both parallel and perpendicular to the regional cleavage; those that are perpendicular to the cleavage are locally openly to tightly folded, with axial surfaces striking NE and dipping NW. The magmatic foliations have a variable orientation (perhaps indicating magmatic processes or a variable strain field; Paterson et al., 1989a, Paterson and Miller, 1998) whereas the tectonic foliations have a more consistent orientation (parallel to the long axis of the plutons).

Near the contacts, the magmatic foliations are not visible due to later tectonic overprinting, except at the NE and SW ends of the plutons, where the magmatic and tectonic foliations are at high angles to each other (Fig. 4). The tectonic foliation is defined by euhedral to kinked books of biotite and attenuated, polycrystalline recrystallized quartz ribbons. Along the NW margin of the Nuka pluton, in McCarty Fiord, the magmatic foliation is clearly parallel with the intrusive margin, whereas along the NE margin of the pluton the magmatic and tectonic foliations are discordant. Lineations defined by aligned hornblende and biotite are developed in some zones, and generally plunge to the north. The magmatic and tectonic fabrics tend to be parallel along the NE/SW-trending concordant margins of the plutons and are at high angles to one another along the NW/SE-trending discordant contacts. This discordance implies that the plastic deformation fabrics cut the magmatic deformation fabrics, and postdate them by some time.

Early Paleogene Seldovia Dike Swarm

The Kenai Peninsula is cut by locally dense, discrete swarms of dikes (Fig. 5G), showing a calc-alkaline differentiation trend and ranging in composition from basalt to rhyolite, with dacite being the most abundant dike composition (Lytwyn et al., 2000; Bradley et al., this volume, Chapter 1). The dikes and ca. 55 Ma plutons have overlapping compositions, but the dikes have a greater range in composition than the plutons (Bradley et al., this volume, Chapter 1). The basalts and basaltic andesites show the most primitive "MORB-like" REE trends (Bradley et al., this volume, Chapter 1), whereas the more evolved dacites and rhyolites show HREE depletion and LREE enrichment, consistent with mixing of melted accretionary prism material with the MORB source magmas (e.g., Harris et al., 1996; Lytwyn et al., 2000; Sisson et al., this volume, Chapter 13). Interestingly, some of the dikes have xenocrystic kyanite and/or garnet, suggesting genesis at depths of 20 km or more. The dikes and plutons are interpreted to be comagmatic based on overlapping isotopic ages and chemistry (Bradley et al., this volume, Chapter 1). The dikes cut mélange fabrics of the McHugh Complex (Fig. 5H) and foliations in the Valdez Group, showing that they are relatively late structural features. A few of the dikes are foliated and possibly folded, but most cut all the fabric elements in the accreted metasediments (Figs. 5I and 5J). On the lower Kenai Peninsula, and east of Anchorage, some of the dikes are spatially related to near-trench plutons. Several dikes have yielded $^{40}Ar/^{39}Ar$ ages of 57–53 Ma (Bradley et al., 2000, 1999), suggesting that the entire swarm may be related to passage of the triple junction that generated the plutons of the Sanak-Baranof belt.

Most of the dikes on the lower Kenai Peninsula strike east-southeast, with minor differences between the basaltic and andesitic dikes (east-west strikes), and the dacite-rhyolite dikes (east-southeast/west-northwest strikes). Two dikes with anomalous Au concentrations strike southeast-northwest (Fig. 6). The significance of these differences is unclear, but could be related to counterclockwise rotations of the stress field during intrusion of progressively differentiated dikes, perhaps with slight difference in time of intrusion. Perhaps more significantly, most dikes indicate extension at about 15° to the regional strike, implying that the stress field operative during dike emplacement differed from the stress field during development of the main Cretaceous structural fabric in the Chugach terrane (Kusky et al., 1997a, 1997b; Kusky and Bradley, 1999; Haeussler et al., this volume, Chapter 5).

Figure 6 presents a regional compilation of dike orientations from the Chugach terrane. In the northern Kenai Peninsula and the Prince William Sound area (Tana Glacier, Valdez, Port Wells), the dikes show about the same orientation with respect to the structural grain, but are more N-S in orientation, suggesting that they have been rotated in the hinge of the southern Alaska orocline (Fig. 6). A paleomagnetic study of the dikes that was aimed at quantifying these rotations (A. Bol, 1992, personal commun.) was inconclusive. Dikes on the western limb of the orocline (Matanuska-Knik area, Eagle River area, Girdwood, Hope-Sunrise District) also strike about N-S, but lie at an acute angle to the local grain. In southeastern Alaska, dikes strike NW, subparallel to the margin and the local structural grain. Except in southeast Alaska, the net effect of dike emplacement was orogen-parallel extension; the cumulative thickness of the dikes suggests perhaps 1% extension was accommodated by dike intrusion.

Circa 35 Ma Plutons in the Prince William Sound Region

A younger, ca. 35–30 Ma suite of plutons intrudes the Chugach–Prince William terranes in the Prince William Sound area (Fig. 3). Plutons of this group include the Terentiev (29.2 ± 0.3 Ma, $^{40}Ar/^{39}Ar$ on microcline; Nelson et al., 1999), Esther (35.5 Ma, K/Ar—biotite; L. Snee, personal commun., 1992), Nellie Juan (36.1 Ma, K/Ar—biotite; L. Snee, personal commun., 1992), and Eshamy bodies (Fig. 2). The Miners Bay pluton (Fig. 3) has yielded $^{40}Ar/^{39}Ar$ age on biotite of 38.6 ± 0.6 to 41 Ma (Nelson et al., 1999), but a dioritic phase of this pluton yielded an $^{40}Ar/^{39}Ar$ age of 59.1 ± 0.1 Ma (Nelson et al., 1999), suggesting that this pluton may be part of the older Sanak-Baranof belt, and be equivalent to the Nuka, Aialik, and other plutons discussed above. These ca. 35 Ma plutons have to-date defied compelling tectonic explanation. We suggest the following scenario as a tentative explanation for their origin. At 40–33 Ma, the ridge was being subducted nearly parallel to the continental margin (see Bradley et al., Fig. 16, this volume, Chapter 1). A small change in the orientation of the ridge in response to the early Eocene plate reorganization (Sisson and

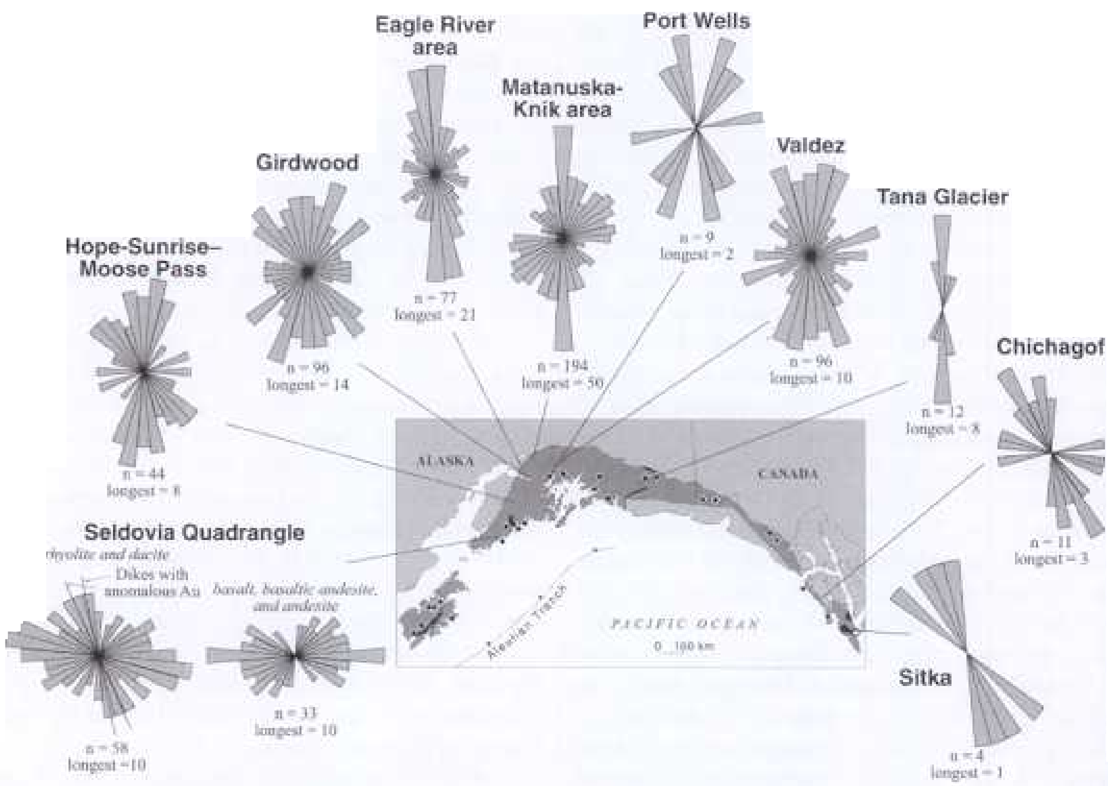

Figure 6. Map of Chugach terrane showing orientation of dikes of Paleocene-Eocene age (after Haeussler et al., this volume)

Pavlis, 1993) would cause it to migrate instantaneously northward, intersecting the continental margin where it curved significantly in southern Alaska (Fig. 2C). The sudden re-appearance of the ridge and slab window in the Prince William Sound area caused a second generation of melting and near-trench magma generation, explaining the ca. 35 Ma plutonism. After this, the rest of the ridge would be subducted in a relatively short time (depending on the geometry of ridge-transform offsets) along western North America. For the purposes of this work, we use the ca. 35 Ma plutons as spatial and temporal markers for the development of structures in the wedge. By determining which structures predate, postdate, and are synchronous with the 55 and 35 Ma plutons, we have two additional constraints on the structural evolution of the accretionary wedge as a whole.

Terentiev Pluton

The Terentiev pluton is a medium- to fine-grained, locally well-foliated, two-mica and amphibole-bearing granite (Nelson et al., 1999). It has yielded a $^{40}Ar/^{39}Ar$ isochron age of 29.2 ± 0.3 Ma (Nelson et al., 1999), interpreted as an exhumation and cooling age from intrusion near 34 Ma. The Terentiev, Granite Cove, and Cedar Bay plutons are enriched in alkalis and silica compared to other ca. 35 Ma plutons in Prince William Sound, consistent with derivation from melting of evolved rocks of the accretionary prism (Nelson et al., 1999). The Terentiev is finer-grained and has more amphibole near its margins and is more quartz-rich at higher structural levels. It has a mottled phase toward the center of the pluton that consists of fine-grained amphibole-rich granite with interstitial pods and zones of coarser-grained two-mica granite. The core of the pluton is a medium-grained two-mica granite with minor and varying amounts of amphibole. Mineral percentages are approximately 20–35% plagioclase, 15–35% orthoclase, 10–25% quartz, 3–7% biotite, 1–4% muscovite, 1–8% amphibole, 1–5% sulfides, and 1–4% opaques, garnet, secondary epidote, and unknowns.

The Terentiev pluton intrudes the Orca Group (Fig. 7), forming a contact aureole of albite-epidote hornfels facies (Nelson et al., 1999), with rare staurolite (Haeussler and Nelson, 1993). In the area of Figure 7, the Orca Group includes units of massive sandstone, turbidites, conglomerate, siltstone, shale, and chaotic deposits interpreted as slump deposits (Nelson et al., 1999). Minor volcanic rocks (Fig. 7) include volcanogenic mudstone with hyaloclastite. These are interbedded with purple to green calcareous shale, thin-bedded pelagic limestone, and tectonically disrupted graywacke-shale units (Nelson et al., 1999; Haeussler and Nelson, 1993).

Magmatic foliations are defined by aligned plagioclase crystals and locally by aligned amphibole crystals. Several separate internal lobes and circular patterns defined by the magmatic foliation can be distinguished within the magma chamber (Fig. 7). Magmatic folds defined by folded magmatic layering are visible both on the outcrop and map scales. These magmatic folds tend to be parallel or subparallel to the margins. The great vertical relief in this pluton (topographically lower in the southeast, higher in the northwest; Fig. 7) revealed a lower zone characterized by lobate magmatic foliations, a higher zone with relatively parallel or tabular foliation traces, and a highest zone containing many blocks of country rock just below a roof pendant.

Pre-emplacement fabrics in the aureole of the Terentiev pluton consist of annealed bedding-parallel faults and ductile mélange fabrics preserved in the biotite-grade hornfels. The first stages of syn-emplacement deformation are represented by pods to tabular zones of intrusion breccia consisting of angular clasts of granite in a very fine-grained green groundmass. The breccia groundmass is geochemically identical to the granite (S.W. Nelson, 1993, personal commun.). To the south of Terentiev Lake a large mass of similar intrusion breccia associated with the Granite Cove granitic stock (Fig. 7) has been dated at 29.2 ± 0.1 Ma ($^{40}Ar/^{39}Ar$ plateau age on K-spar: Nelson et al., 1999). Tabular zones of intrusion breccia in the Terentiev pluton are parallel to several other structures, including early epidote/quartz veins, later iron oxide/quartz veins, relatively late NW-striking sinistral faults, and an EW-striking normal fault set. These faults are parallel to, and may be part of the late orthorhombic fault set that Kusky et al. (1997a) related to ridge subduction.

The long axis of the Terentiev pluton is parallel to NW-striking sinistral faults in the surrounding Orca Group (Figs. 7 and 8). These faults are probably part of the ca. 55 Ma regional set of orthorhombic faults (Fig. 8F) that Kusky et al. (1997b) related to late stages of Paleogene ridge subduction. The Terentiev pluton seems therefore to have intruded at ca. 35–30 Ma along extinct fault sets formed during ridge subduction at ca. 55 Ma, soon after this part of the Orca Group was accreted. The magmas likely used the old faults as structurally weak planes to intrude along, forming intrusive contacts where faults previously existed. Several NW-striking faults also cut the Terentiev pluton. Slickensides on the dominant NNW-striking sinistral fault set show changes in orientation with time. Early motions along these faults (preserved in the epidote/quartz veins) had a significant dip-slip component whereas younger FeO/quartz veins record a progressive trend towards strictly strike-slip motion (plunges on the last set are approximately 1°–4°). These relationships are similar to those of the 55 Ma ridge-subduction related orthorhombic fault set at Turnagain Arm.

The Terentiev pluton is also cut by NE-striking dextral fault zones, which are the youngest structures recognized, and postdate all plutonism. These are typically several centimeters to meters wide zones of fault gouge, with several tens of centimeters to meters (or more) displacement. Haeussler and Nelson (1993) note that several ca. 35–30 Ma plutons in the Prince William Sound area are cut by very late dextral faults including the Contact fault.

The magmatic and tectonic structures present within the Terentiev pluton and its associated contact aureole can be attributed to the subduction of the western plate (oceanic plate B), which was the "trailing" plate of a migrating, subducting spreading ridge. Pre-emplacement fabrics, though not thoroughly studied in this area, are consistent with subduction

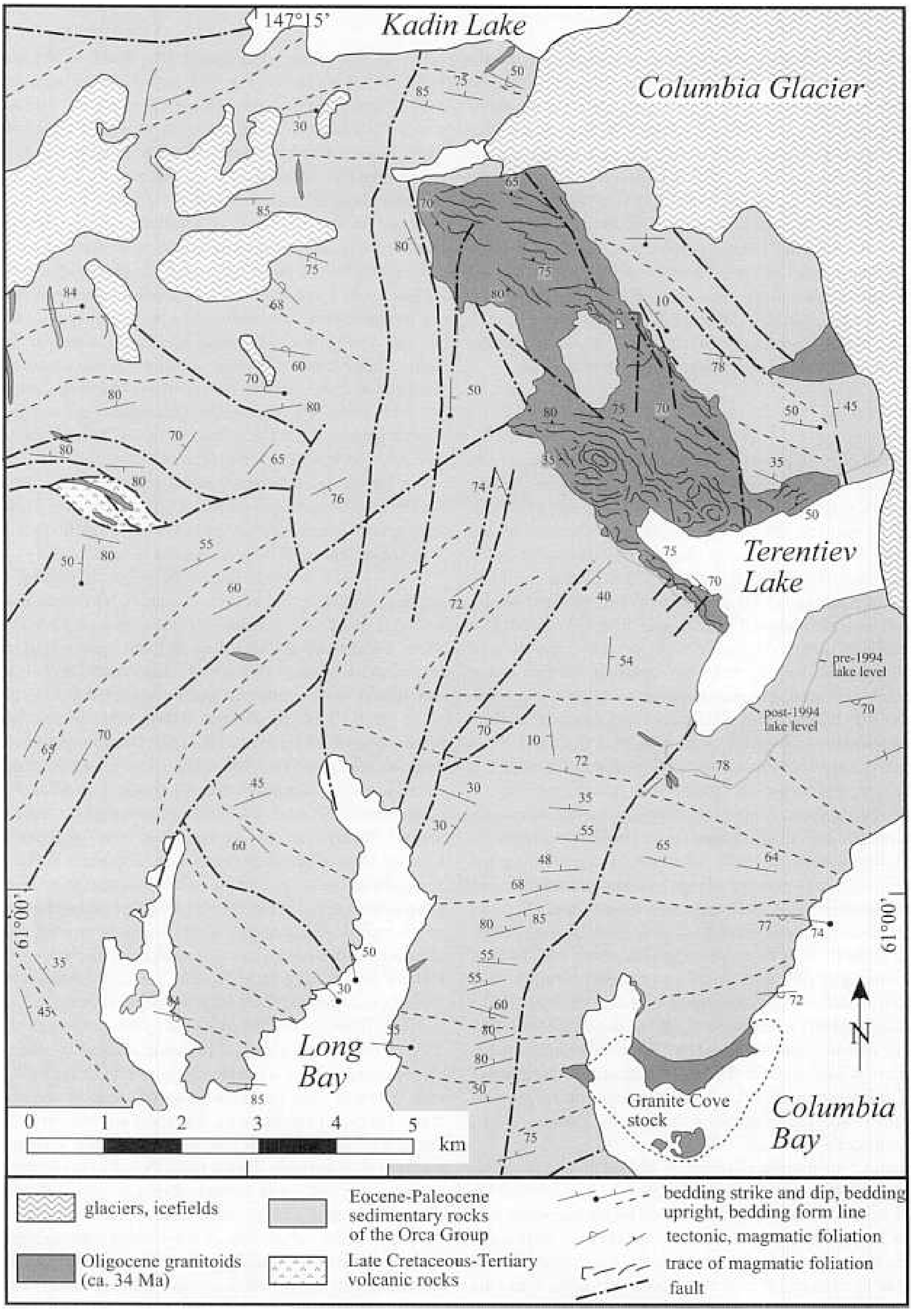

Figure 7. Map of the ca. 30 Ma Terentiev pluton and surrounding Orca Group (compiled from Nelson et al. (1999), and 1:6000 scale mapping of magmatic foliations by authors). Map emphasizes relationships between magmatic and tectonic foliations.

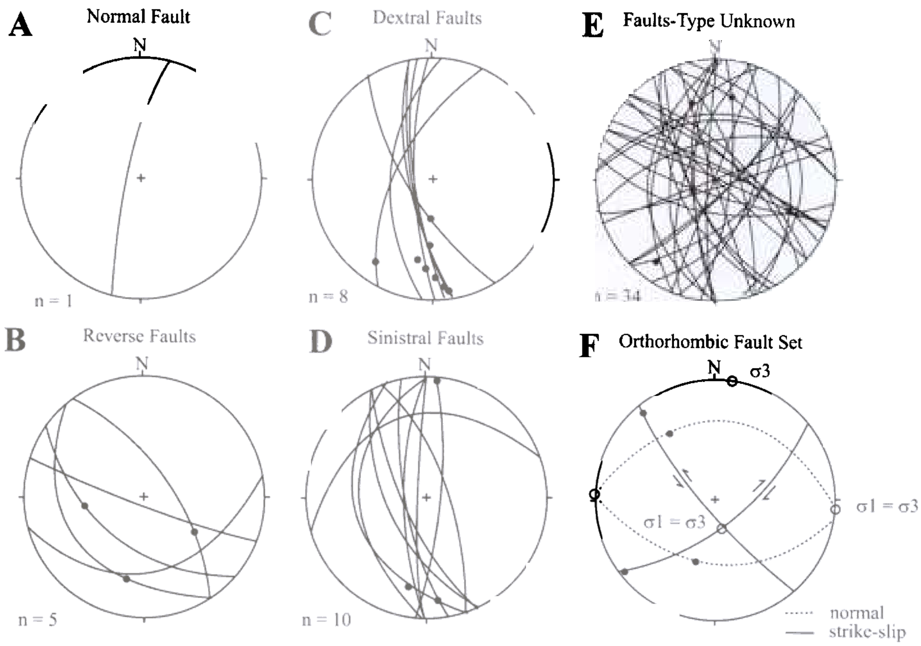

Figure 8. Structural data (after Haeussler and Nelson, 1993) from the Columbia Glacier–Terentiev pluton area, showing the orientation of normal (A), reverse (B), dextral (C), sinistral (D), and unknown faults (E). F: Geometry of Paleogene orthorhombic fault set from the Turnagain Arm area (from Kusky et al., 1997b). Note that Terentiev pluton is elongate parallel to the sinistral faults of the regional orthorhombic set, and to sinistral and thrust faults in the study area.

kinematics interpreted from along strike (Kusky and Bradley, 1999) and include evidence for layer-parallel extension. Synemplacement fabrics are apparently restricted to the plutonic body. These fabrics include magmatic foliations that define magmatic lobes and folds near the contact with the country rock. The contact zones are characterized by abundant angular metasedimentary xenoliths that typically have their long axes parallel to the contact. In some cases there is a strongly bimodal size distribution of the xenoliths, in which case the small ones have their long axes parallel to much larger xenoliths, which in turn have their long axes parallel to the contact with the country rock. Late-stage emplacement related structures through postemplacement fabrics include intrusion breccia dikes, high- and lower-temperature late magmatic veining, and brittle faults. It is possible that the intrusion breccia is related to a late magmatic (Granite Cove stock?), highly volatile explosive stage. The dominant near field mechanism for magmatic emplacement for the Terentiev pluton appears to be diking and thermal shattering forming stoped blocks near the magma/host rock contact. The origin of the lobes defined by the magmatic foliations is less clear; they could be magmatic diapirs, or they could represent complex folds formed in a crystal-liquid mush due to strain being concentrated in the crystallizing magma chamber.

Eshamy and Nellie Juan Plutons

The ca. 35 Ma Eshamy pluton (Fig. 3) consists of a series of thin dikes parallel to regional orogenic strike, but perpendicular to the long axis of the pluton. It is a multi-pulse pluton composed of a series of individual sheets or dikes (e.g., Hibbard and Watters, 1985), with a sequence of crosscutting relationships indicating a magmatic series from gabbro to quartz-feldspar porphyry to biotite-hornblende granodiorite to gabbro to granite. It is a fairly shallow-level intrusion, based on spectacular fracturing and stoping along the pluton–wall rock boundary. Xenoliths are especially abundant along the pluton's southwestern end. Based on our reconnaissance observations, we conclude that the Eshamy pluton was probably never a large body of magma, but represents a magma pathway that was active for many batches of melt, with at least two generations of gabbro generated at depth (from the slab window?), explaining the repetition of compositional pulses. This distinction is important, because it suggests that the Eshamy was never a single batch of magma, but represents a time series of dikes, a couple of meters wide at a time, striking parallel to regional strike, then cut by a NE cleavage. The Eshamy pluton bears many similarities to other multiple-pulse, sheet-like intrusions including the Calamity Peak Complex in the Black Hills (Duke et al., 1988). In contrast, the Nellie Juan pluton is extremely homogenous, with only a weak transitional magmatic/solid state foliation parallel to regional strike.

MAGMATIC EMPLACEMENT MECHANISMS

The style of magmatic emplacement during ridge subduction can be evaluated through interpretation of field relationships, the structure of the plutons, mineralogy, and metamorphic reactions (e.g., Castro, 1987). The Nuka and Aialik plutons form a series of granitic-to-granodioritic sheets that strike approximately 020° along their long sides, and have a variety of dips, predominantly steeply northwest. The magmatic layers, however, curve along with the pluton contacts, forming discordant contacts with country rocks along their short NW-striking margins. Most contacts are relatively planar and utilize pre-existing anisotropies and fabrics within the Valdez Group. The Tustumena–Harris Bay pluton strikes NNW and shows stronger magmatic deformation fabrics than the other plutons, suggesting that its intrusion is largely controlled by a NNW striking shear zone. Isotopic studies of pluton-related quartz veins (Goldfarb et al., 1986; Borden et al., 1992; Taylor et al., 1994) indicate emplacement at 5.2–10.5 km depth and 210–300 °C. The regional metamorphism of the Valdez group is lower greenschist facies, and the contact aureole is cordierite-biotite (amphibolite) grade, also indicating that the plutons were emplaced in a shallow (approximately 3–25 km for lower greenschist facies) and cool (~250–450 °C) part of the accretionary prism. Since the plutons have megacrystic kyanite apparently concentrated along their contacts, the peraluminous melt must have been generated at a depth of at least 20 km at a minimum temperature of 650 °C, in the PT space where the stability field of kyanite is above the granitic solidus (e.g., Essene, 1986; Hibbard, 1995). Therefore the melt must have migrated upward to its emplacement level of less than 5.2–10.5 km from at least this depth, entraining the kyanite and other xenocrystic phases along its intrusion path. If the kyanite crystals were in contact with the melt, then the magma must have risen at a rapid rate that would prevent the kyanite from recrystallizing to a more stable aluminosilicate or phyllosilicate. However, the reaction rims around the kyanite crystals effectively isolated them from reacting with the melt.

Relationships of Plutons to Regional Structures

The intrusion of many granitic bodies is triggered by some kind of tectonic activity, and understanding specific triggers is one of the fundamental goals of many granite studies (e.g., Leake, 1990; Petford et al., 2000). The large plutons of the Sanak-Baranof belt on the Kenai Peninsula and Kodiak Island are predominantly oriented slightly oblique to the main terrane-bounding faults and large-scale regional strike. They are generally parallel to local foliations and bedding traces. In particular, the Kodiak batholith, the composite Tustumena–Harris Bay plutons, and the large pluton near Mt. Tom White in the Bearing Glacier quadrangle (eastern Chugach Mountains; Fig. 1) are all elongated about 15°–45° counterclockwise from the main bounding faults of the Chugach terrane (Fig. 9). The Nuka and Aialik plutons are elongate parallel to regional strike, and are associated with regional scale lineaments parallel to or coincident with known faults (Fig. 3).

Many plutons are emplaced into dilational bends in strike-slip fault systems (e.g., Hutton, 1987, 1988; Hutton et al., 1990; Hutton and Reavey, 1992; Tobish and Cruden, 1995; Saint Blanquat et al., 1998). Examples include the Main Donegal granite (Hutton, 1982), the Mount Peyton pluton of Newfoundland (Kusky et al., 1987), the Doctor's Flat pluton, Victoria, Australia (Morand, 1992), and many Sierra Nevadan plutons (e.g., Tikoff and Saint Blanquat, 1997; Tikoff et al., 1999). The Nuka and Aialik plutons exhibit sheets and dikes along their contacts, as predicted for plutons whose intrusion is controlled by space opened by active faulting (Yoshinobu et al., 1998). The Chugach terrane experienced a change in kinematics from predominantly head-on convergence to dextral transpression with the passage of the triple junction, and this change formed dextral strike-slip faults in the forearc that are coeval and slightly younger than an orthorhombic fault set formed during ridge subduction (Kusky et al., 1997b). Therefore, a fault-controlled pull-apart mechanism may have controlled the intrusion of the Nuka and Aialik plutons at 55 Ma, which are situated along possible extensional jogs along traces of one of the numerous orogen-parallel strike-slip faults, including the Contact fault (Fig. 9). This mechanism does not, however, explain the Tustumena–Harris Bay pluton, whose long axis is oblique to regional strike.

The long axis of the Tustumena–Harris Bay pluton is parallel to NW-striking sinistral late faults of the ca. 55 Ma orthorhombic fault set on the Kenai Peninsula (Fig. 9; Kusky et al., 1997b). We suggest that a fault of the orthorhombic set may have provided a structural weakness along which magmas of the Tustumena–Harris Bay pluton intruded, largely replacing the fault with an intrusive contact. The area of the sharp bend in the Tustumena–Harris Bay pluton preserves an unusually strong NW-striking tectonic foliation (Fig. 5E) that we interpret as related to this shear zone.

Tikoff and Teyssier (1992) propose an alternative pluton emplacement model for transpressional arcs that may have applications to the Sanak-Baranof belt. In their model, plutons are emplaced into en echelon P-shear tensional bridges, forming elongate plutons oriented approximately 15° from the main orogenic strike. P-shears (Logan et al., 1979) form at low angles to the main transpressional structures in rheologically simple, brittle systems. R-shears may connect individual P-shears, and movement on the crustal scale shear system creates extensional jogs into which magmas may be emplaced. However, it is unknown how applicable this general model may be to rheologically complex systems like the southern Alaska forearc, nor is it known how these P-shears and related fractures may connect with ductile structures at depth. In the model of Tikoff and Teyssier (1992), the spacing and the amount of overlap between individual P-shears determines the shape of the individual plutons. P-shears commonly have a large overlap area resulting in elongate plutons oriented with their long walls parallel to the P-shears (Tikoff and Teyssier, 1992). Additionally, the largest strains should be on the margins of the plutons along the P-shears, and most foliations in the plutons should be nearly vertical and parallel to the P-shears (Tikoff and Teyssier, 1992).

Some of the field relationships in the Sanak-Baranof belt are apparently explained by this alternative model. The orientations of the many plutons are parallel to the hypothetical P-shears, and the pluton emplacement mechanisms point to fracture-controlled intrusion. In the case of the southern Kenai Peninsula, however, it is difficult to identify specific structures that may be P-shears or R-shears, whereas most pluton-related structures correlate with the main dextral strike-slip faults or the orthorhombic fault set. However, other P-shears may be obscured by intrusion by the

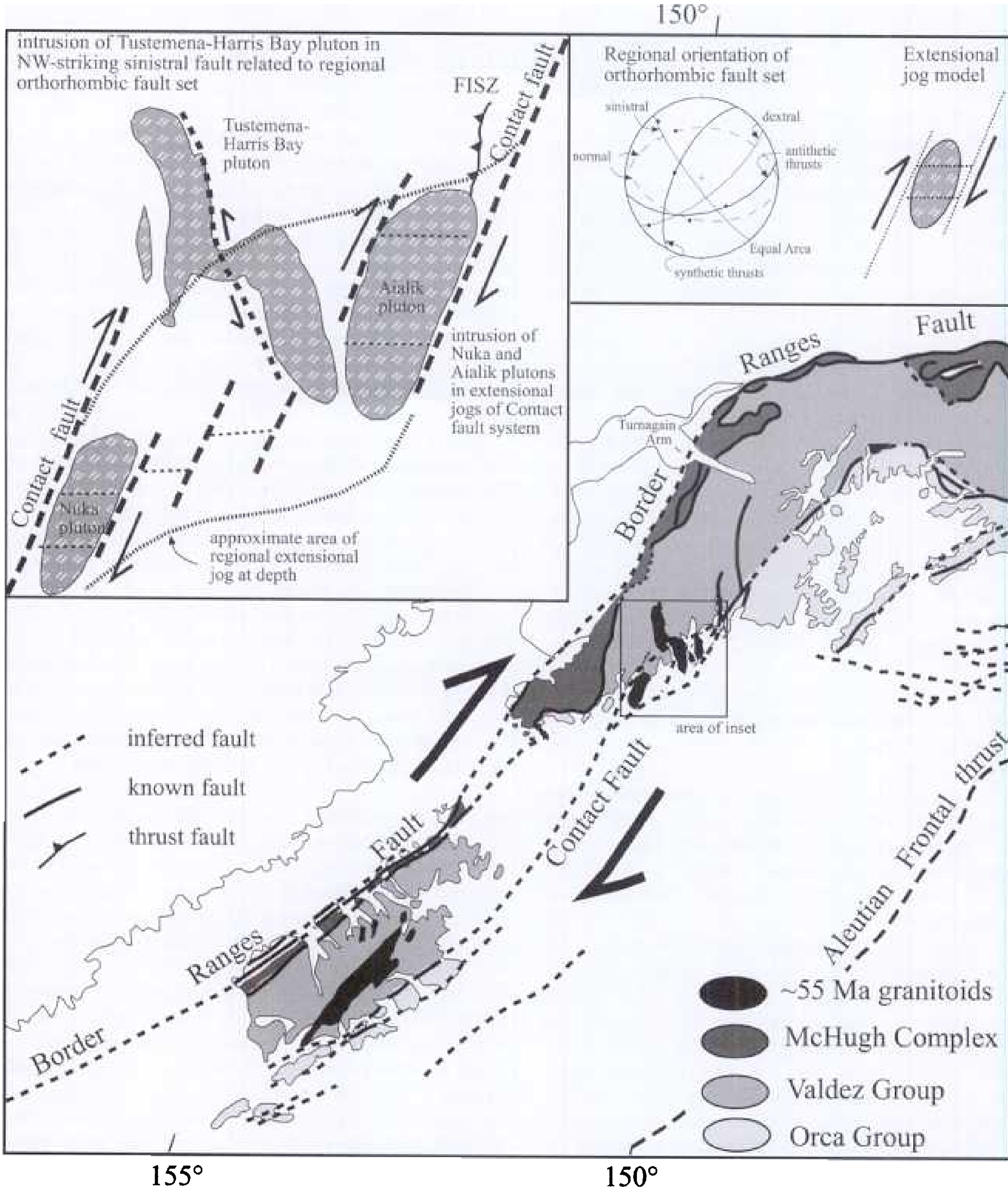

Figure 9. Map showing relationship of plutons to orthorhombic fault set. The Nuka and Aialik plutons are elongate parallel to orogen-parallel strike-slip faults and are interpreted to have intruded into dilational jogs during movement on these faults. The Tustumena–Harris Bay pluton is parallel to and deformed by NW-striking sinistral faults of the ridge-subduction-related orthorhombic fault system, and probably used these faults as a structural weakness to ease intrusion into the wedge.

granites, i.e., plutonism lagged behind faulting, and the plutons merely used pre-exisiting faults as planes of weakness to intrude along. Other faults may be covered by glaciers, outwash, or may be only exposed at the bottoms of deeply incised fiords. The lack of identifiable P-shears may also be partly attributable to the fact that the region has only been mapped at the reconnaissance scale of 1:250,000. Nonetheless, we note the well-exposed shear zone in the Tustumena pluton may continue along its margin to the north, and that several of the deep fiords that mark the boundaries of the plutons are parallel to the predicted P-shear direction (e.g., McCarty Fiord, Harris Bay, Aialik Bay, and Resurrection Bay). In addition, the southern margin of the Tustumena pluton is abruptly terminated along a glaciated valley parallel to the predicted R-shear direction.

One variation of the fault-related intrusion mechanism is preserved on Hive Island and Ragged Island in Resurrection Bay. Here, the northwestern side of the Aialik pluton appears to have been emplaced along a thrust fault (Fox Island shear zone; FISZ in Fig. 4) that formed during emplacement of the Resurrection Peninsula ophiolite between 57 and 53.4 Ma as a consequence of ridge subduction (Kusky and Young, 1999). This thrust fault may have intersected one of the deep-seated shear systems at depth, and magma migrated along the fault. Such migration of magmas along an active rapidly moving thrust, with the consequent melt-enhanced deformation (e.g., Karlstrom et al., 1993; Yoshinobu et al., 1998) could explain the rapid emplacement of the Resurrection Peninsula ophiolite.

Use of the circa 56 Ma Plutons as Strain Markers, to Estimate Plate Kinematic Parameters Before, During, and After Ridge Subduction

We use the ca. 56 Ma plutons of the Sanak-Baranof belt as time and strain markers, separating kinematic regimes that predate, postdate, and were synchronous with ridge subduction. The suite of 35–30 Ma plutons in Prince William Sound provide an additional time and strain marker that can be used in the same context. Any structures related to ridge subduction will be late features (Paleogene), superimposed on fabrics related to early accretion, but perhaps contemporaneous with structures resulting from coastwise strike slip and/or orocline formation. Structures associated with magma emplacement (for the ca. 56 Ma plutons and dikes) are regarded as related to ridge subduction, whereas the chronology of other structures is established by crosscutting relationships. We have placed considerable emphasis on establishing which structures cut the 56 Ma plutons, and which cut or are cut by the ca. 35 Ma plutons.

We emphasize the sequence of development of late structures, paying particular attention to the relative timing of deformation and near-trench magmatism. Hypersolidus fabrics produced by magmatic flow and deformation of hot plutons are differentiated from crystal-plastic fabrics, which are entirely post-crystallization (e.g., Marre, 1986; Paterson and Tobish, 1988; Paterson et al., 1989a, 1989b, 1991).

Relative Timing of Pluton Emplacement and Fabric Development

Pre–circa 56 Ma Pluton Emplacement Structures

Structures and fabrics associated with Late Cretaceous subduction present in the Valdez Group includes regional scale, northeast-trending isoclinal folds; bedding and cleavage are generally parallel to one another (Kusky et al., 1997b). The mélange of Iceworm Peak is a type-1 mélange that forms a regionally mappable unit along the contact between the McHugh Complex and the Valdez Group. Kinematic analysis of the fabric elements that are cut by ridge-subduction related dikes led Kusky et al. (1997b) to suggest that the pre–triple junction interaction contraction and convergence was close to perpendicular to the paleo-trench, during subduction of oceanic plate A (Farallon or Resurrection) beneath the Chugach terrane.

Minor faults related to accretion and subduction of the oceanic plate A are also preserved in the contact aureole of the Nuka, Tustumena–Harris Bay, and Aialik plutons. The dominant style of deformation was orogen-parallel extension (Figs. 4A and 4B). The orientations of these extensional slip surfaces are consistent throughout the contact aureole (345°, 85°W) and reflect bedding-parallel extension perpendicular to the maximum compression direction. These extensional slip surfaces also cut the fabric of the Iceworm mélange and are therefore post-Maastrichtian (age of Valdez protolith to Iceworm mélange) and older than 57 Ma (age of crosscutting dike) (Kusky et al., 1997a). There are other early dip-slip faults that are at a higher angle to bedding that are cut by dikes and therefore also predate ridge subduction. The pre-ridge subduction faults reflect E-W contraction and N-S extension, perhaps formed during early dewatering and volume loss during early accretion (e.g., Kusky and Bradley, 1999).

Syn–circa 56 Ma Pluton Emplacement Structures

Structures associated with emplacement of the Nuka, Tustumena–Harris Bay, and Aialik plutons and subduction of the spreading center include brittle/ductile faults, foliation development and porphyroblast growth in contact aureoles, and brittle dikes. Dikes associated with the emplacement of the plutons (in close proximity to the pluton margins) have been boudinaged and folded. Dikes oriented subparallel to the pluton margins are boudinaged, whereas dikes oriented at a high angle to the shear direction are ptygmatically folded. This relationship suggests that the plutons expanded or ballooned during intrusion, superimposing a local strain upon the regional strain field (e.g., Bateman, 1984, 1985; Paterson, 1988; Paterson and Vernon, 1995). The fact that not only the dikes but also the lithified graywackes are ductilely deformed (post-mélange and post-bedding-parallel brittle faults) suggests that the cold accretionary prism must have experienced a significant localized thermal softening event, consistent with the cordierite-biotite (amphibolite) metamorphic grade of the aureole. It is unlikely that these fabrics are post emplacement since the rheological contrast between the low-grade Valdez Group and the metamorphic aureole would have resulted in a strain partitioning and localization of deformation at the margin of the aureole and not ductile shear zone formation within the aureole.

The plutons have a strong tectonic fabric at their margins and a weakly developed tectonic foliation away from their margins. This is because the margins, having cooled faster than the interior of the plutons, were able to preserve tectonic fabrics, whereas the more liquid interior of the pluton did not preserve fabrics related to this phase of deformation. A melt that is greater than 55% solidified experiences a dramatic increase in viscosity due to crystal locking and will support a shear stress (Arzi, 1978; Scaillet et al., 1997). The mostly crystalline melt could therefore have foliations related to tectonic/syn-emplacement strains. This tectonic/syn-emplacement foliation is also developed within later-stage, syn-emplacement, crosscutting dikes as well (Fig. 5J). This strain is the result of both regional and local emplacement stresses (e.g., Yoshinobu et al., 1998).

Post–circa 56 Ma Pluton Emplacement Structures

Post-emplacement brittle fabric patterns are more complex because, in some instances, the later faults have reactivated older faults. In an effort to distinguish between reactivation of pre-existing faults and the creation of new fracture surfaces, careful selection of brittle faults for measurement was made. The bulk of the orientations in Figures 4C and 4D reflect faults mapped in the Nuka, Tustumena–Harris Bay and Aialik plutons and those in the contact aureoles that were observed to crosscut the pluton or dikes, or in a few cases earlier brittle to ductile features. There is a set of conjugate strike-slip faults but most faults are high-angle normal faults and lower-angle reverse/thrust faults. Post ridge subduction deformation is marked by an orthorhombic fault system (three dip-slip and two strike-slip). The dip-slip faults have orientations of N40°E, 80°E for the normal faults, N20°E, 10°E and N40°E, 70°W for the reverse faults while the strike-slip faults have orientations of 335°, 85°E for sinistral faults and N60°E, 75°NW for the dextral faults. These are similar to the syn-ridge subduction orthorhombic fault set described from the Turnagain Arm area by Bradley and Kusky (1990) and Kusky et al. (1997b), although rotated slightly. The presence of these faults in the plutons shows that the stress system that formed the orthorhombic fault set persisted though the late-ridge subduction related plutonism, and that the faults and plutons are spatially and temporally related.

These late faults, formed during subduction of oceanic plate B (Kula) indicate a significant component of dextral transpression, associated with orogen-perpendicular extension that is probably related to exhumation and critical taper recovery following ridge subduction (Kusky et al., 1997b).

Additional Constraints on Structural History of the Wedge from circa 35 Ma Plutons

The Terentiev pluton intruded the Orca Group along a set of fractures that is similar in orientation to both the late faults and the orthorhombic fault set described from the Valdez Group by Kusky et al. (1997b). Emplacement along this pre-existing weakness may explain the anomalous NW elongation of the Terentiev pluton. The Terentiev pluton is cut by numerous NE-striking dextral strike-slip faults, showing that dextral transpression continued past 30 Ma.

CONCLUSIONS

Physical evidence from the Nuka, Tustumena–Harris Bay, and Aialik granitic complex and surrounding rocks has implications for ridge subduction and intrusion mechanisms of near-trench magmas associated with ridge subduction. The granites of the Harding Icefield region were intruded into a fault network within the accretionary prism and these faults include orogen-parallel strike-slip faults as well as an orthorhombic fault set including NW and NE striking strike-slip faults. Xenocrystic kyanite and garnet indicate that the magmas were generated above 650 °C at pressures exceeding 5.5 kbars (>20 km; Fig. 10). Metamorphic mineral assemblages, isotopic and fluid inclusion studies indicate that the plutons intruded at 5.2–10.5 km depth, into wall rocks at 210–300 °C. Several of the plutons appear to have intruded along NW-striking sinistral faults of the orthorhombic fault set, formed at an angle to the main regional dextral shear system developed as a consequence of ridge subduction (Fig. 10).

Structures present in the contact aureoles of the Nuka, Tustumena–Harris Bay, and Aialik plutons that can be attributed to deformation prior to the subduction of the oceanic ridge include regional NE-striking thrusts, folds, and zones of ductile to brittle layer-parallel extension (mélange foliation and bedding-parallel normal/listric faults). There are also two conjugate sets of larger, brittle dip-slip faults that may occur at higher structural levels in the accretionary prism.

Syn–56 Ma pluton emplacement deformation includes strains related to intrusion and expansion of plutons and intrusion of swarms of dikes throughout the region. The dikes generally strike at a high angle to regional bedding and cleavage and reflect a component of orogen-parallel extension at a high angle to the main orogen-parallel strike-slip faults. Intrusion of most of the magmas related to ridge subduction seems therefore to be controlled in some way by the large-scale orogen-parallel faults. Plutons intruded into extensional jogs along the main faults, oblique fracture systems related to the orthorhombic fault set, and dikes intruded at high angles to the faults and reflect extension in the same direction.

Post–56 Ma pluton emplacement deformation includes high-angle normal and lower-angle reverse/thrust faults. The normal faults strike at approximately 040° and dip near vertical. The reverse faults have a similar strike but dip shallowly to the southeast and less commonly steeply to the northwest. There is also a less common and well-developed conjugate set of strike-slip faults. Together, these late fault sets possess orthorhombic symmetry, and are remarkably similar in orientation to the late ridge subduction related orthorhombic fault system documented from the Turnagain Arm area (Kusky et al., 1997b). Overall,

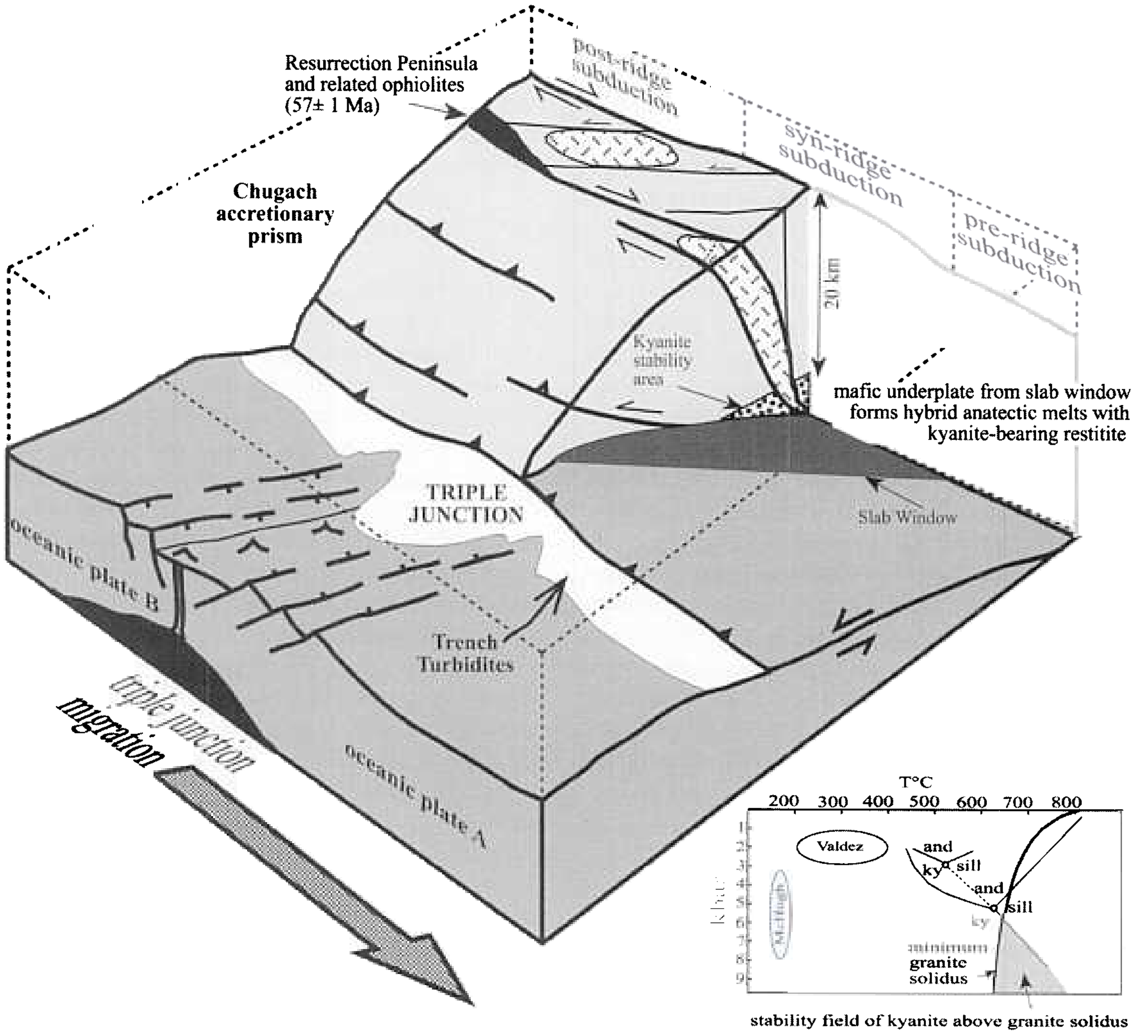

Figure 10. Three-dimensional sketch indicating the relative position and timing of ridge subduction, formation of the slab window, generation of the Nuka-Aialik and Harris Bay plutons, and activation of the late out-of-sequence thrust faults including the Fox Island shear zone.

this orthorhombic fault set accommodated dextral oblique transpression, with $\sigma_1 = \sigma_2$ about WNW-ESE axes, along with extensional faulting in the upper part of the wedge accommodating exhumation in response to recovery of critical taper after ridge subduction (Kusky et al., 1997b).

The suite of 35–30 Ma plutons in Prince William Sound is interpreted to have formed in response to the ridge migrating back northward in response to the early Eocene plate reorganization (Fig. 2). These plutons add an additional temporal strain marker that is used to calibrate the structural evolution of the wedge. Post-30 Ma pluton emplacement deformation includes margin-parallel dextral strike-slip faulting, probably associated with the northward translation of the Chugach terrane with respect to North America.

Implications for Forearc Evolution and Crustal Growth

Recognizing the Sanak-Baranof belt as a product of ridge subduction has several implications for forearc evolution and the interpretation of linear belts of plutons in ancient mountain belts. Forearcs are not necessarily places characterized exclusively by high-P, low-T metamorphic series and a lack of plutonism, but may contain high-T, low-P metamorphism in association with belts of plutonic rocks if the forearc was affected by ridge subduction. Similarly, belts of magmatic rocks in ancient mountain belts may not necessarily represent individual arc terranes, but could be a paired arc/forearc system that experienced a ridge subduction event. The record of ridge subduction events may vary considerably in individual examples depending on the plate geometry and rates of triple junction and slab window migration. However, some of the hallmark signatures of ridge subduction in forearcs include along strike diachronous intrusion of tonalitic, trondhjemitic, granodiorite, to granitic plutons, high-temperature metamorphism, and diachronous gold mineralization, and belts of anomalous complex faulting. We have shown in this contribution how the near-trench magmatic rocks may serve as diachronous temporal and strain markers that separate kinematic regimes in the forearc that represent interactions of the leading and trailing subducting plates with the overriding plate. We have also provided several examples of how faults can control pluton emplacement, both as inactive zones of structural weakness, and as active dilational bends.

Structural, thermal, and magmatic aspects of the Chugach terrane are similar to the geology of Archean greenstone-granodiorite terranes (Pavlis et al., 1988; Kusky, 1989; Barker et al., 1992; Kusky and Polat, 1999). In both, deformation is locally melt-dominated, and plutons follow a low-K series from diorite to trondhjemite (Pavlis et al., 1988). Metamorphism is of a high-temperature low-pressure series. Ridge subduction was most likely an important process in the Archean, when the total number of plates was higher, and the number of ridge-trench encounters was probably greater (Kusky and Polat, 1999). The southern Alaska margin then may serve as a relatively "modern" example of processes that were likely to have been important in Archean forearc evolution and continental growth.

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